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Measurement of the Properties of Lossy Materials Inside a Finite Conducting Cylinder

by

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Broadband, swept frequency measurement techniques were investigated for the evaluation of the electrical performance of thin, high temperature material coatings. Reflection and transmission measurements using a HP8510B Network Analyzer were developed for an existing high temperature test rig at NASA Lewis Research Center. Reflection measurements will be the initial approach used due to fixture simplicity even though surface wave transmission measurements would be more sensitive. The minimal goal is to monitor the electrical change of the material's performance as a function of temperature. If possible, the materials constitutive parameter, ε and μ will be found.

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Chapter 1

Introduction

Modern material treatments on metallic structures have to perform and survive in a variety of environments. One practical environment has hot flowing gases heating the material treatment. NASA Lewis Research Center presently operates a test rig to evaluate the mechanical survivability of a material coated metal plate in a confined region. The confined region consists of a circular pipe with hot jet gases being directed at a coated plate in its interior. The material so far has been evaluated mechanically through repeated heat cycles. The highest temperature of interest is approximately 1800° F. It would be reasonable that the electrical properties of the material change during the heat cycles, especially when such high temperatures are of interest. An effort is underway to develop measurement techniques centered around the present test rig at NASA Lewis Research Center to monitor the electrical characteristics of material coatings on metal plates.

The ElectroScience Laboratory (ESL) has developed a variety of techniques applicable for such measurements using time domain technology. The use of time domain techniques is essential for the above task since electromagnetic energy in a closed region will be multiply reflected and most certainly corrupt any measurement unless range gating techniques are applied. The basis is to use these techniques to isolate the mechanisms associated with the material of interest from all other mechanisms and thus be able to better interpret the measured data in terms of the material properties.

The goal has been to develop these measurements at the ESL in the absence of the hot flowing gases and then to assist in the development of a hardened system as needed. It is envisioned that the hardened system will measure the desired electrical characteristics in the absence of the hot air flow and repeat the appropriate measurements in the presence of the hot air flow at the various temperatures of interest. It would be desirable to measure the absolute value of these electrical properties but this is not practical due to the lack of the required absolute calibration references. The minimum achievable goal has been to measure any changes in the electrical (consequently mechanical) properties of the lossy materials.

However, the major effort in this program has been concerned with the design, development, construction and testing of the required apparatus. This report discusses the practical electromagnetic measurement techniques that have been evaluated.

Chapter 2

Material Evaluation

The electrical performance of a material treatment on a conducting surface can be evaluated by either monitoring the reflected signal from the surface or the surface wave through the material. Ideally, the monitoring is best accomplished if the material parameters, ϵ_r and μ_r, can be determined. This can be accomplished if the performed measurements are adequately calibrated and there is an analytical model for the measured quantity including the dependency of the material parameters. Two alternative approaches in monitoring the material performance are to characterize the relative energy of the reflected field from a material treated plate or the relative attenuation of a surface wave.

There are two traditional measurements possible being, reflection and transmission from a material interface or through the material, respectively. In any measurement, it is always desirable to have the sensing fields interact sufficiently with the material. The material test sample is a thin coating over a metal surface which can limit the sensitivity for a reflection measurement. A transmission measurement can permit greater material interaction but its sensitivity can be limited in adequately exciting surface waves.

The determination of material complex parameters, ϵ_r and μ_r, requires four independent equations involving these parameters. Traditionally, this has entailed reflection and transmission measurements at each frequency of interest with each measurement supplying two independent values (real and imaginary). When the parameters are not highly frequency dependent, a reflection or transmission measurement will suffice. The most obvious practice is to perform two measurements at slightly different frequencies. Another approach is to integrate the measured values, $M(\omega)$, around the frequency of interest ω_o such as

$$\overline{M}(\varepsilon_r, \mu_r) = \int_{\omega_o-\Delta\omega}^{\omega_o+\Delta\omega} M(\omega, \varepsilon_r, \mu_r) \left[.5 \cos \frac{\pi}{2} \left(\frac{\omega_o - \omega}{\Delta\omega}\right) + .5\right]^n d\omega$$

to provide two other indepedent values from the real and imaginary parts of $\overline{M}$. The shifted cosine function performs a simple weighted average process resulting in a noise reduction of the measured signal. Such an integration can provide another independent relationship when the material parameters are functionally different such as is the case for a coated planar metal surface. The reflected wave for a plane wave normally incident upon the coating is given by

$$R(f, t, \varepsilon_r, \mu_r) = \frac{j\eta_r \sin(kt) - \cos(kt)}{j\eta_r \sin(kt) + \cos(kt)}$$

where f is the frequency, t is the coating thickness, the relative material wave impedance $\eta_r = \sqrt{\frac{\mu_r}{\varepsilon_r}}$ and the material wave number $k = 2\pi f \sqrt{\mu\varepsilon}$.

This approach would be convenient since then only one measurement type would be required. A major drawback in actually determining the electrical parameters with the test rig is providing an adequate reference to calibrate the measurements discussed in the next chapter. The HP-8510B can be calibrated before a heat cycle test of a material sample but the system as a whole can drift during the test due to thermal expansion of the test rig.

Another aspect in determining the material parameters is having a rigorous reflection or transmission model. Only the reflection technique has a simple analytical model involving the complex material parameters, ε_r and μ_r.

An alternate approach to monitor the electrical performance of the material treatment is calculating the energy of the reflected or transmitted signal. This calculation is simply equal to the sum of the squared signal samples in the time domain.

The third approach to monitor the electrical performance of the material treatment requires one or two transmission measurements using probes. The surface wave has a functional form given by

$$A\frac{e^{-\gamma d}}{\sqrt{d}}$$

where A is some constant, $\gamma = \alpha + j\beta$ is the sum of the attenuation constant and the phase constant, and d is the distance between the probes. A relative measure of the loss in a material during a test could be acquired since γ is dependent upon ε and μ. However, this measure would not be applicable between different material samples due to the dependence that A would have. This limitation can be eliminated by taking two measurements with different probe distances. The propagation constant can be obtained by taking the ratio of two transmission measurements where the probe separation distances are different for each measurement assuming everything else is constant. The propagation constant is given by

$$\gamma = \frac{-\ln\left(\sqrt{\frac{d_1}{d_2}}\frac{M_1}{M_2}\right)}{(d_1 - d_2)}$$

where $d_{1,2}$ are the probe separation distances, and $M_{1,2}$ are the measured transmission values. This γ is still relative and a measurement of a material with a known γ would have to be performed to scale the measured γ. The material's parameters could also be found with a calibrated γ but there would be better success with a reflection measurement.

Chapter 3

Measurement Hardware

All the measurements and initial data processing will be performed using the HP-8510B Network Analyzer [1]. This instrument has the capability to perform the necessary swept frequency reflection and transmission between 2 and 18 GHz. Although the instrument is already heavily automated, an external HP-300 series PC will be used as a controller for the HP-8510B to initiate a desired measurement sequence, perform any signal processing and for data storage. The HP-8510B is a unique instrument, for it can perform a variety of useful processing techniques on the acquired data. An essential feature is the frequency to time domain transformation capability. This permits the exclusion of undesired reflected and transmitted signals in the measurement to recover the frequency response of the desired quantity. This time domain concept will be demonstrated in the following section.

The hardware configuration for the HP-8510B will not be in the standard mode. The configuration is illustrated in Figure 3.1 as proposed by Jim Cusick of NASA Lewis. This hardware layout was primarily dictated by the operating conditions in the test rig room and to have the basic analyzer portion of the HP-8510B available for other applications during inactive periods of the test.

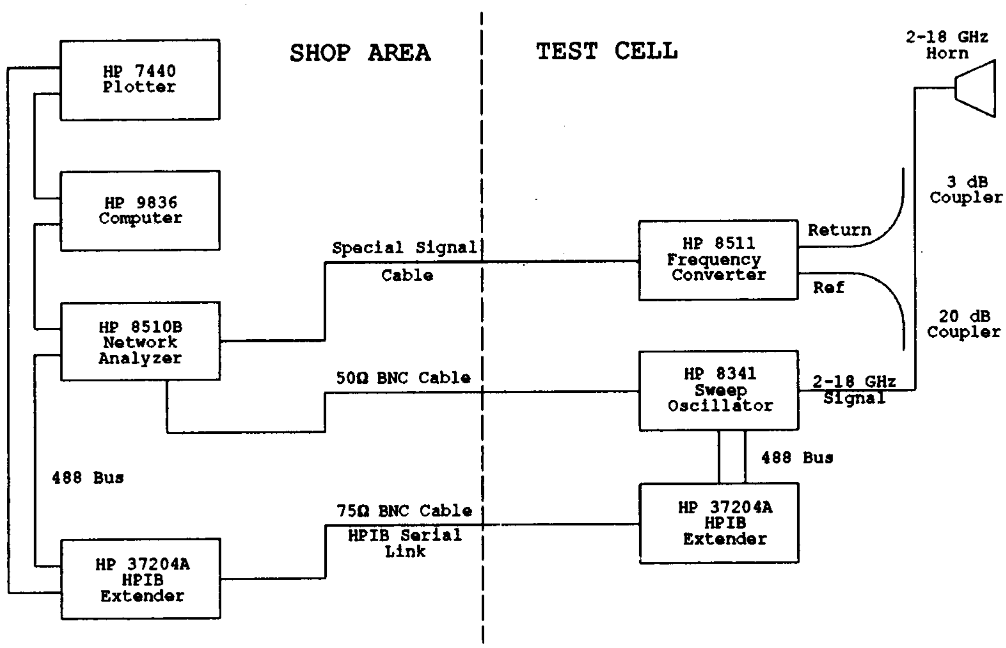

Figure 3.1: Proposed hardware configuration for the HP-8510B Network Analyzer.

Chapter 4

Measurement Techniques

There are a variety of measurements possible to sense changes in the electrical characteristics of a material using reflection and transmission concepts. The main difficulty of performing such measurements in the desired high temperature environment is to supply a RF signal for the illumination or excitation of a wave in the test rig. Figure 4.1 illustrates a modified section of the existing test rig to incorporate the means to electrically monitor a test sample of material. A test section based upon the drawing in Figure 4.1 has been designed at W.L. Tanksley and Assoc., Inc [2]. As shown in Figure 4.1, an electromagnetic horn is used as one means to illuminate the test sample. This is a wide band horn (2-18 GHz) manufactured by AEL [3]. The horn proved to be functional at elevated temperatures before it failed at approximately 900° F. during a reflection measurement. The actual test rig section incorporates air and water cooling to maintain the base of the horn below 200° F..

Other methods of illuminating a test sample by means of a slotted coaxial line or waveguide proved not to couple or radiate well, to be too narrow banded and to be thermally too unstable. However, a high temperature cable was found to deliver a high temperature region with RF in the 2-18 GHz band. This cable, manufactured by ERD[4], would survive these elevated temperatures and provide reasonable electrical performance. The cable construction uses a silicon dioxide powder to support the inner conductor which forces the cable to be hermetically sealed since the powder is hygroscopic. This cable has an application in the transmission measurements to be discussed later. Figure 4.2 illustrates a proposed probe assembly for such transmission measurements. The cable would actually form part of the probe which would penetrate the material sample.

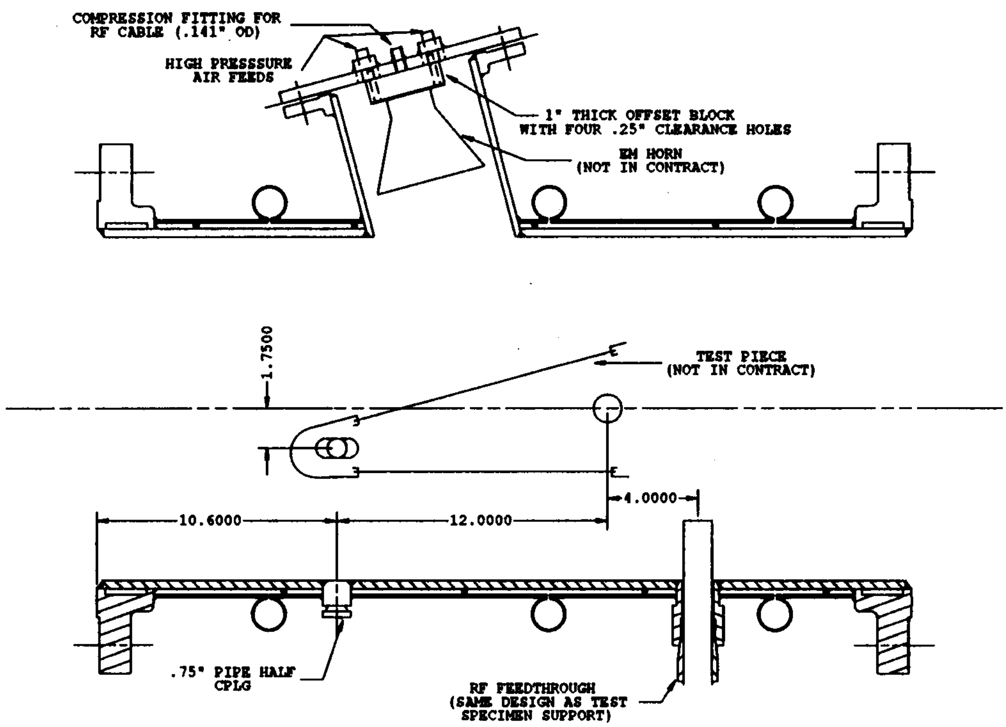

Figure 4.1: Illustration of test fixture for reflection and transmission measurements.

Figure 4.3 shows the test fixture with the HP-8510B Network Analyzer which has been used to evaluate the potential measurement techniques. The test fixture has comparable physical dimensions to the actual section being built for the test rig. It has an appendage similar to the one shown in Figure 4.1 for the AEL horn. The test fixture also has a sample holder similar in size and location as will the actual test rig section. All known relevant aspects of the geometry and conditions were simulated to develop

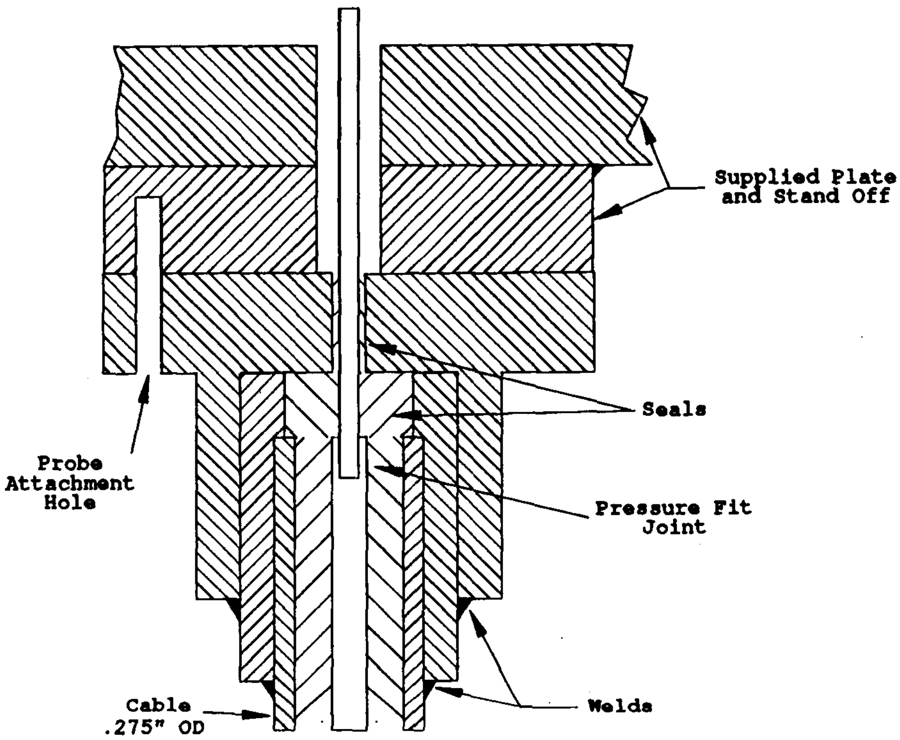

Figure 4.2: Illustration of a high temperature probe connection to a test plate.

the measurement technique and software to perform the measurements. The capability of performing automated measurements between 2 and 18 GHz to monitor the electrical performance of material treatments was the main design criterion for development of these measurement approaches.

The measurements using the HP-8510B Network Analyzer has to be calibrated for material parameter determination. The calibration process requires two steps for absolute measurement values. The first calibration would involve the HP-8510B Network Analyzer using a short or a through reference for a reflection or transmission measurement, respectively. This calibration is sufficient if relative measurements are going to be obtained. The second calibration would involve the measurement of a known sample to scale the material measurements. The reflection measurement has the simplest reference of using the time gated return from an untreated metal test sample.

The actual material coating to be evaluated will be approximately 40 mils thick on a one foot square test plate. The test plate was simulated as shown in Figure 4.3. The material treatment used in the measurements was Standard Emerson and Cuming's rubber loaded radar absorber SF-9 material (50 mils thick).

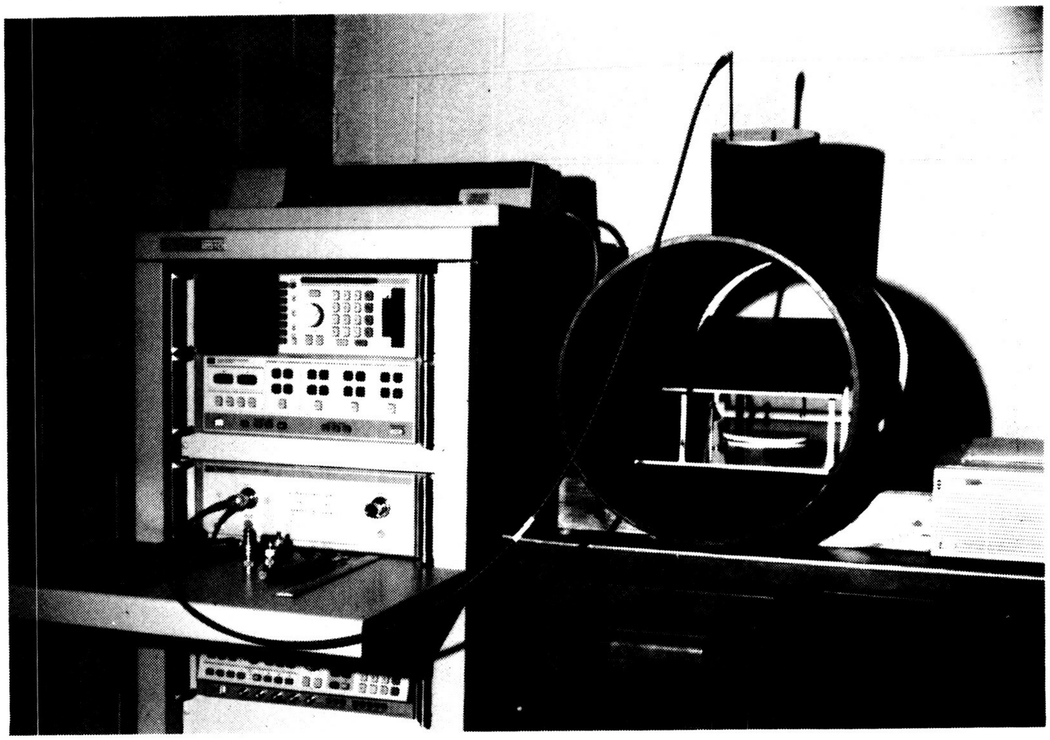

Figure 4.3: Test fixture at the ElectroScience Laboratory for measurement concept evaluation at room temperature.

I Reflection Measurement

A reflection measurement of a coated metal plate can be performed by two approaches for this geometry. One approach is to use the broadband AEL horn in the appendage in the new test rig section. The other approach is

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to use a probe such as the one shown in Figure 4.2. Using the horn as the radiating element has two significant advantages over the probe. One advantage is a much better impedance match is possible over the 2-18 GHz band which relates to having a better signal to noise ratio. The other advantage is a potentially better calibration scheme exists if a horn is used. An untreated plate can be used to calibrate the reflected signal when a horn is used.

Figures 4.4 and 4.5 show the frequency and time domain responses for the measured reflected signal using a probe assembly without and with the Emerson and Cuming's material, respectively. The time domain gated response due to just the reflected signal at the probe aperture is shown in Figures 4.6 and 4.7. The probe was constructed from semi-rigid cable and inserted into a .141" diameter drilled hole which tightly held the cable. The inner conductor was permitted to extend .0625" above the test plate sample with the outer conductor flush to the illuminated side of the metal support plate. The reflected signal is sensitive to the aperture environment as seen in the figures. The measurement sensitivity is poor for the lower portion of the spectrum but improves to a useful range as the aperture becomes electrically large. Another disadvantage for this technique is a good calibration reference and a simple analytical model is not readily available and more difficult than for the following reflection measurement technique.

A more realistic approach is to make a reflection measurement using a horn. Figures 4.8 and 4.9 show the frequency and time domain responses for the measured reflected signal using a horn without and with the Emerson and Cuming's material. The time domain gated response due to just the reflected signal at the material interface is shown in Figures 4.10 and 4.11. A 70 percent reduction of the reflected signal is shown for the measured material in the time domain representation. A good figure of merit for the material's performance would be the sum of the squared time domain data. A calibration reference for this approach would simply be an untreated metal test sample. This calibration measurement would be performed at the start of a heat test. It is unknown at this time how accurate the reference would be during the operation of the NASA Lewis test rig due to the temperature dependence of the physical dimensions which the reference would be sensitive to.

II Transmission Measurement

A transmission measurement of a coated metal plate can be performed by two approaches for this geometry. One approach would be to transmit and receive a RF signal through the material using both the AEL horn and the probe assembly. The other would be to use at least two probes to excite and receive a surface wave along the coated metal surface. The latter approach has the advantage of being more sensitive to the material parameters than the former approach because of greater field-to-material interaction. The major drawback in either transmission measurement is coupling efficiency of the cable's aperture. The aperture of the coaxial cable will not radiate efficiently until its effective probe height is approaching one quarter wavelength and its effective probe diameter is approximately one-half wavelength which occurs above 18 GHz. The aperture size can be increased by using open ended waveguides which have been tested and perform well but are narrow banded and are not physically desirable for high temperature applications.

The transmission measurement results for the two surface probes separated 3 and 6 inches apart in the metal test plate are shown in Figures 4.12 and 4.13. Figure 4.14 illustrates the frequency response of time domain gated signals for the dominant surface wave. These curves demonstrate the poor coupling due to the small aperture size. Figure 4.15 shows the time gated signals for the dominant surface wave when Emerson and Cuming's material is placed on the test sample support with the probe separation distances of 3 and 6 inches. The received signal for the two separation distances almost has a constant offset over the entire frequency band with and without a material coating. Maintaining the same constant offset in the received signal with the material coating as without indicates the measurement values were still in the dynamic range of the HP 8510B.

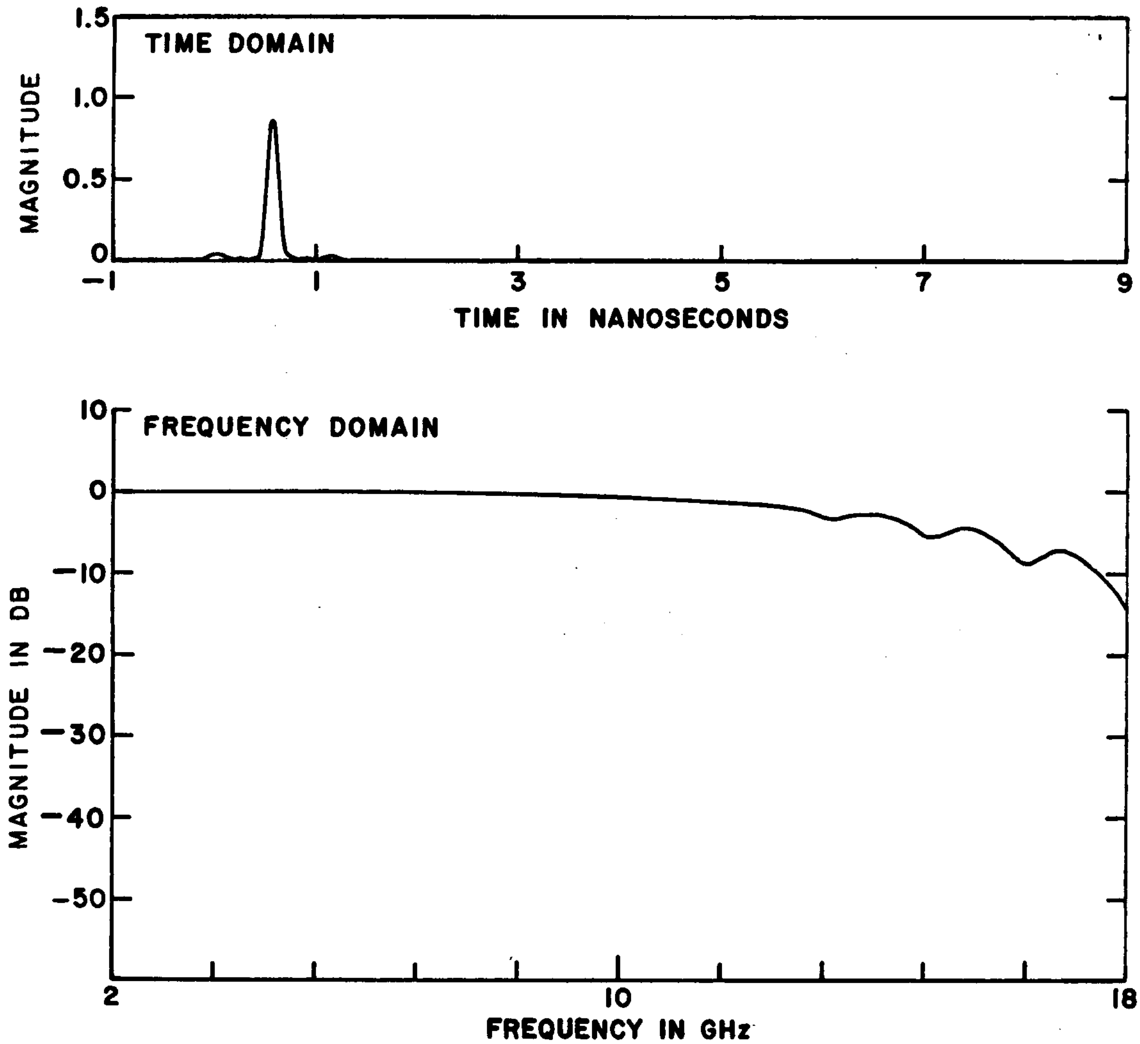

Figure 4.4: The measured reflected signal using a probe feed with no material treatment on the metal test sample support plate.

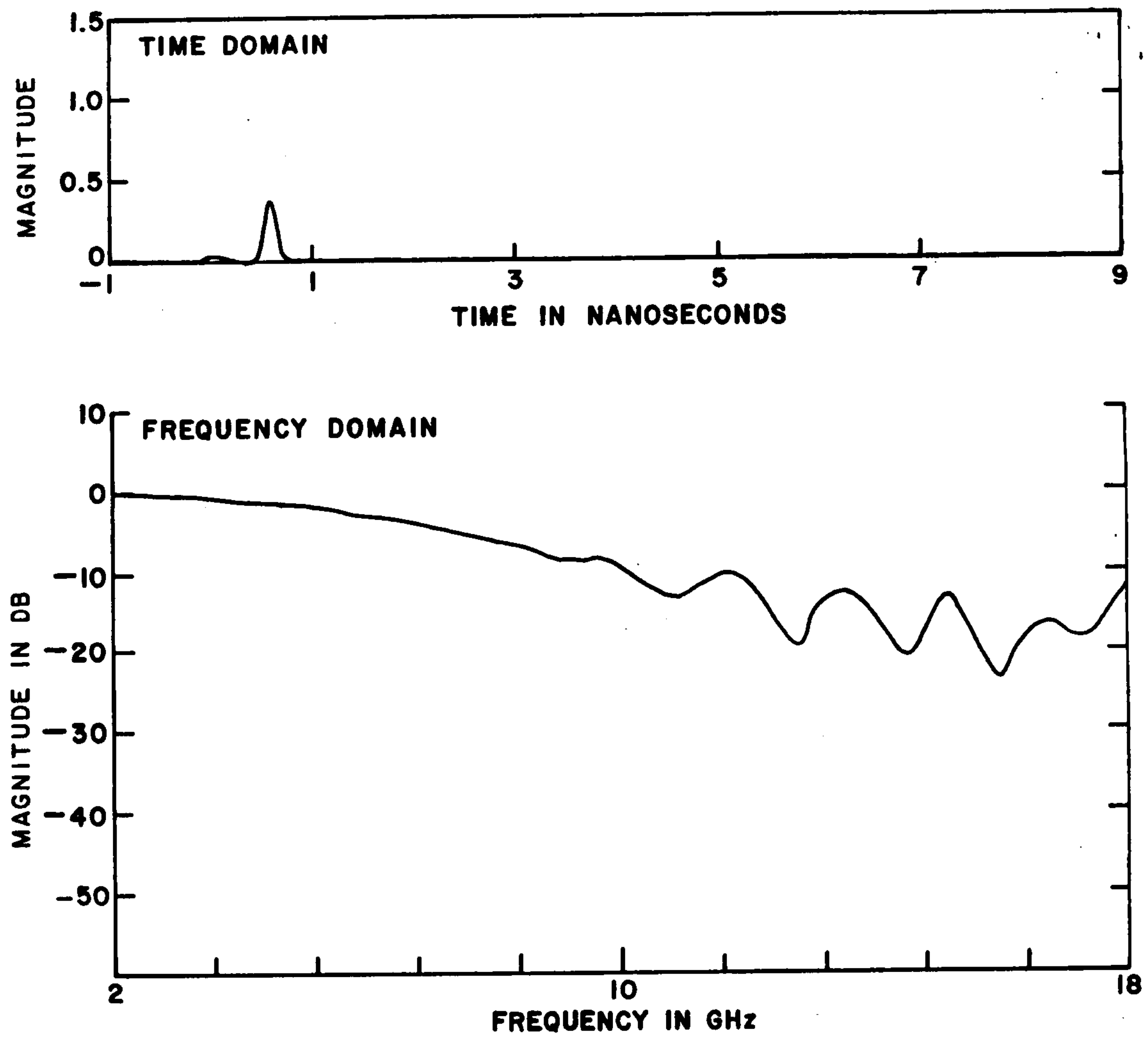

Figure 4.5: The measured reflected signal using a probe feed with material treatment on the metal test sample support plate.

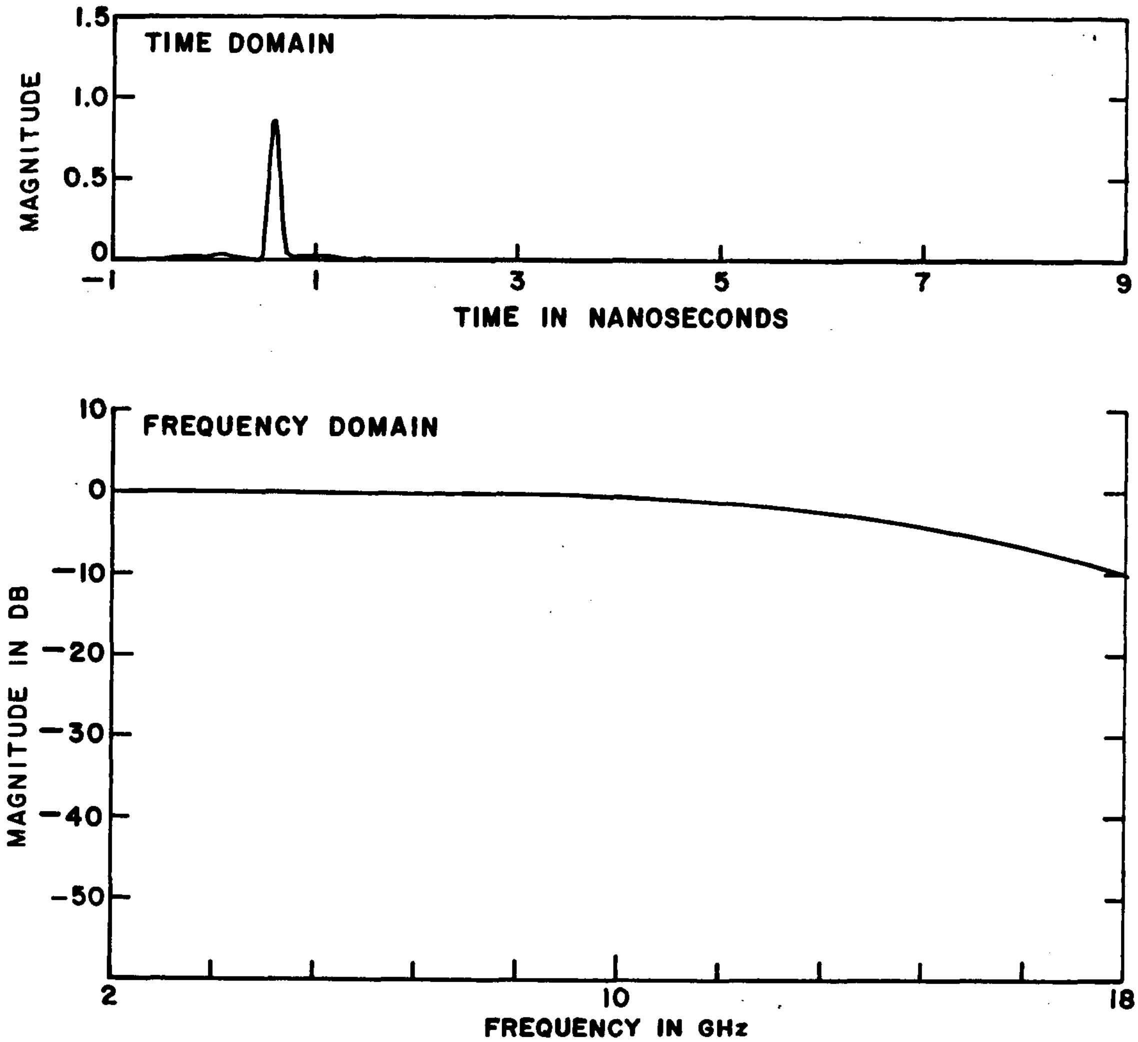

Figure 4.6: The measured, time gated reflected signal at the probe aperture with no material treatment on the metal test sample support plate.

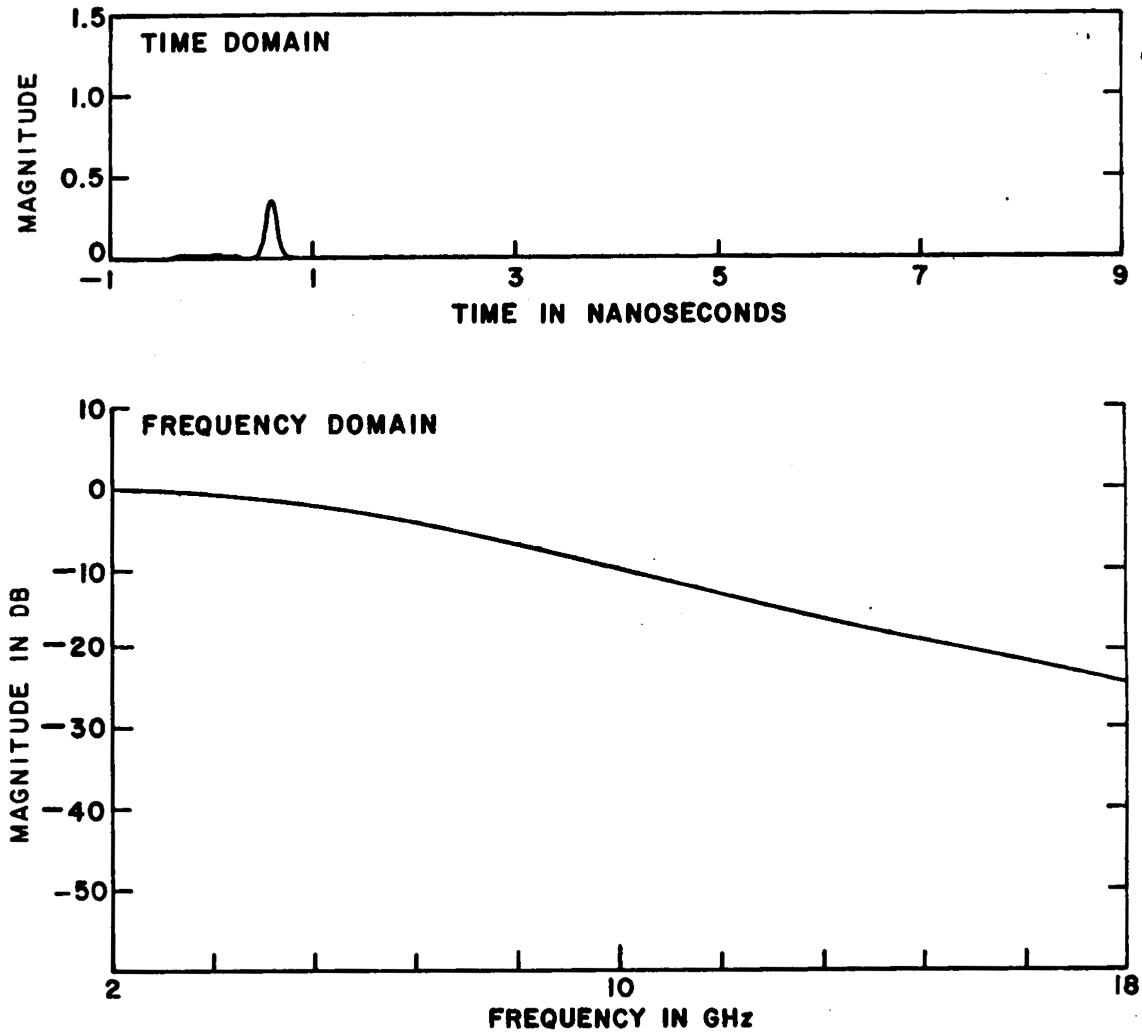

Figure 4.7: The measured, time gated reflected signal at the probe aperture with material treatment on the metal test sample support plate.

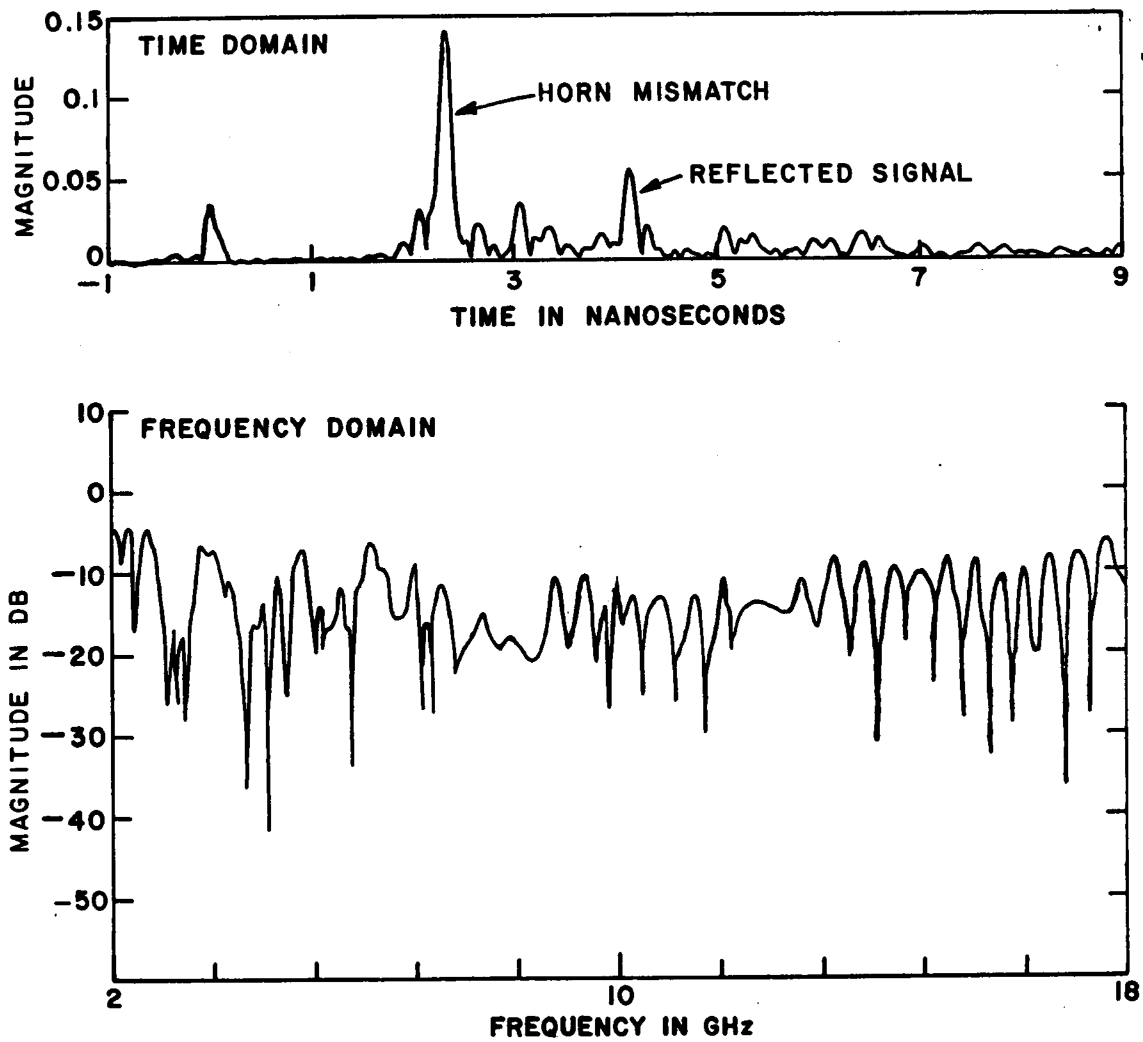

Figure 4.8: The measured reflected signal using a horn feed with no material treatment on the metal test sample support plate.

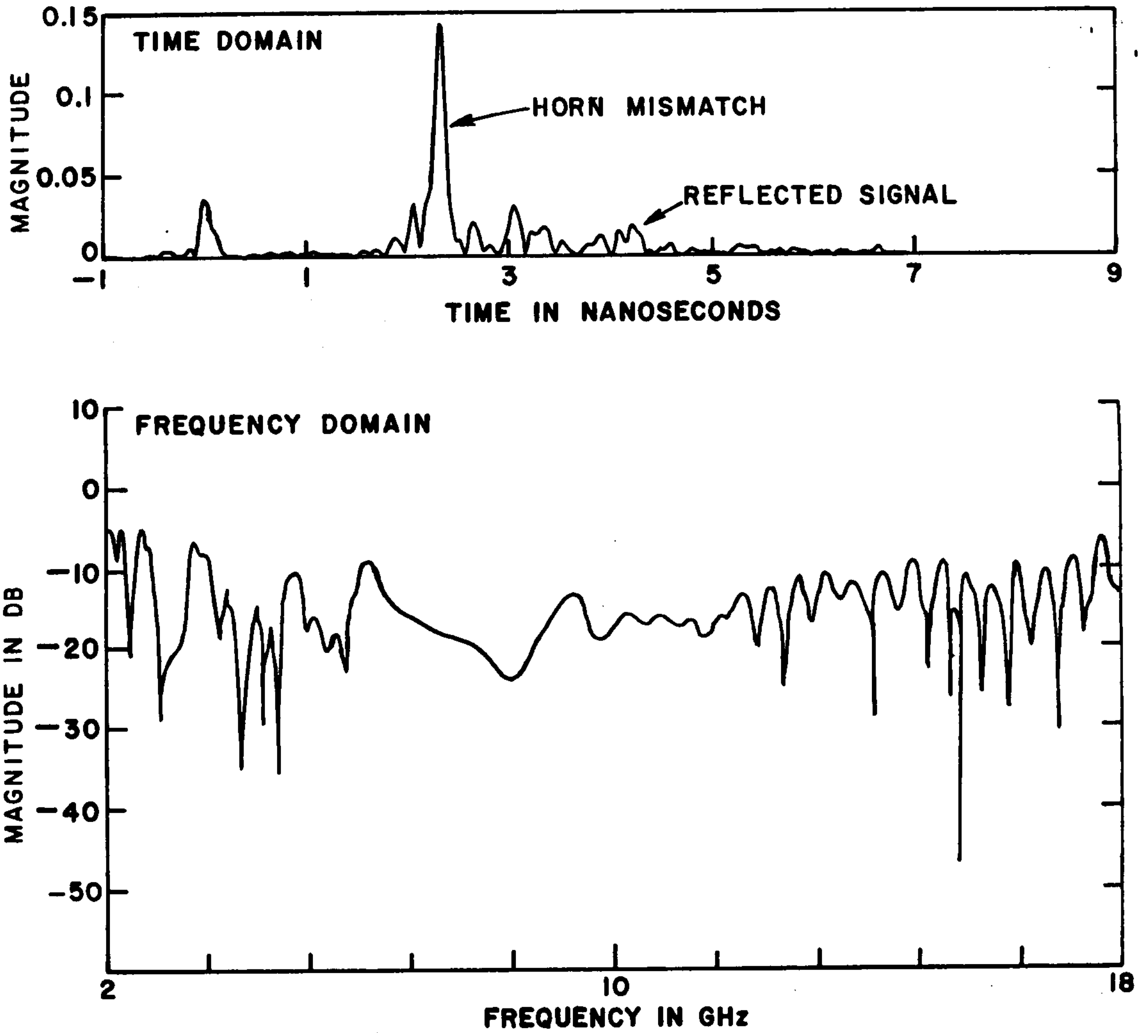

Figure 4.9: The measured reflected signal using a horn feed with material treatment on the metal test sample support plate.

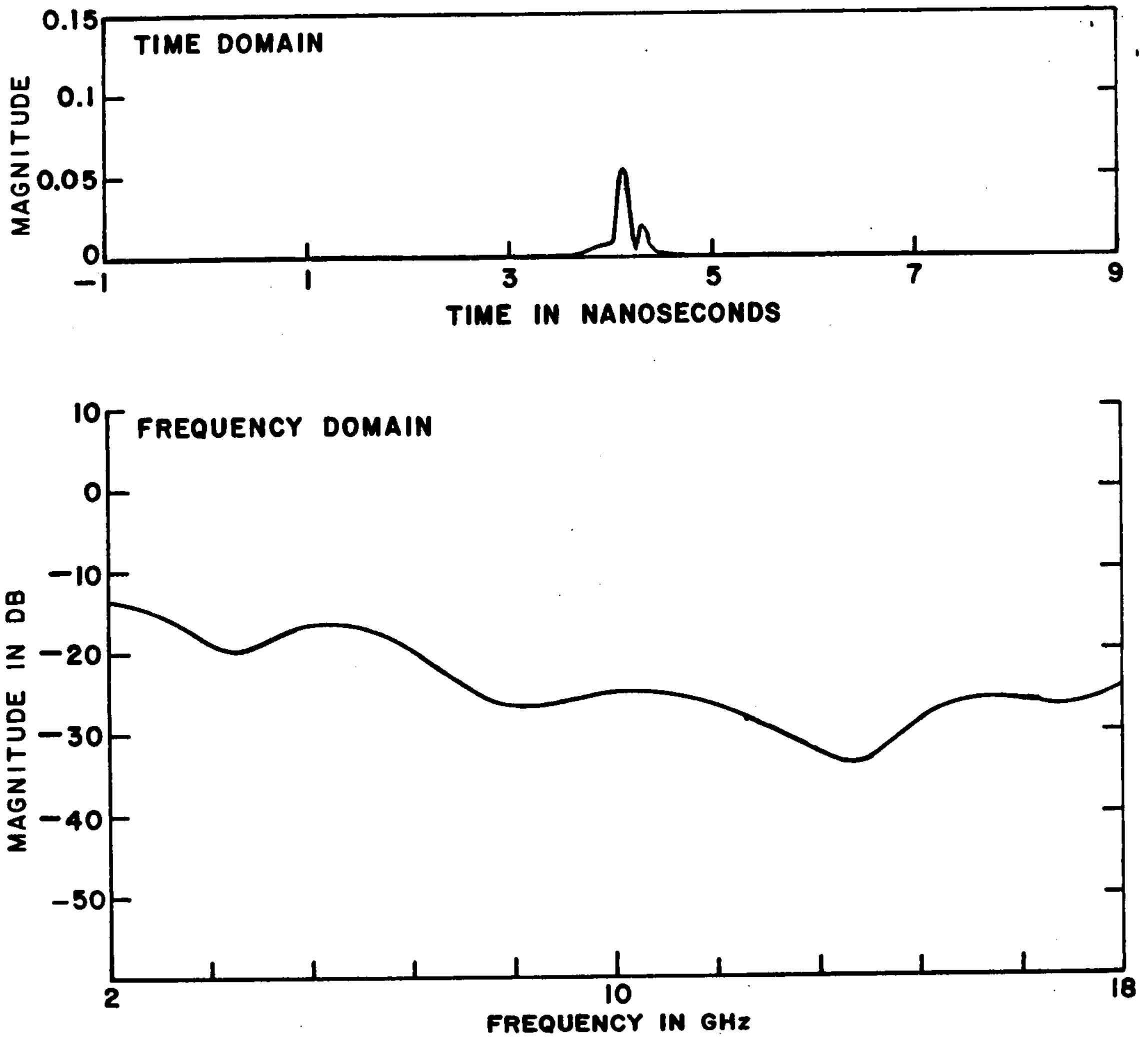

Figure 4.10: The measured, time gated reflected signal from the metal test sample support with no material treatment using the AEL horn.

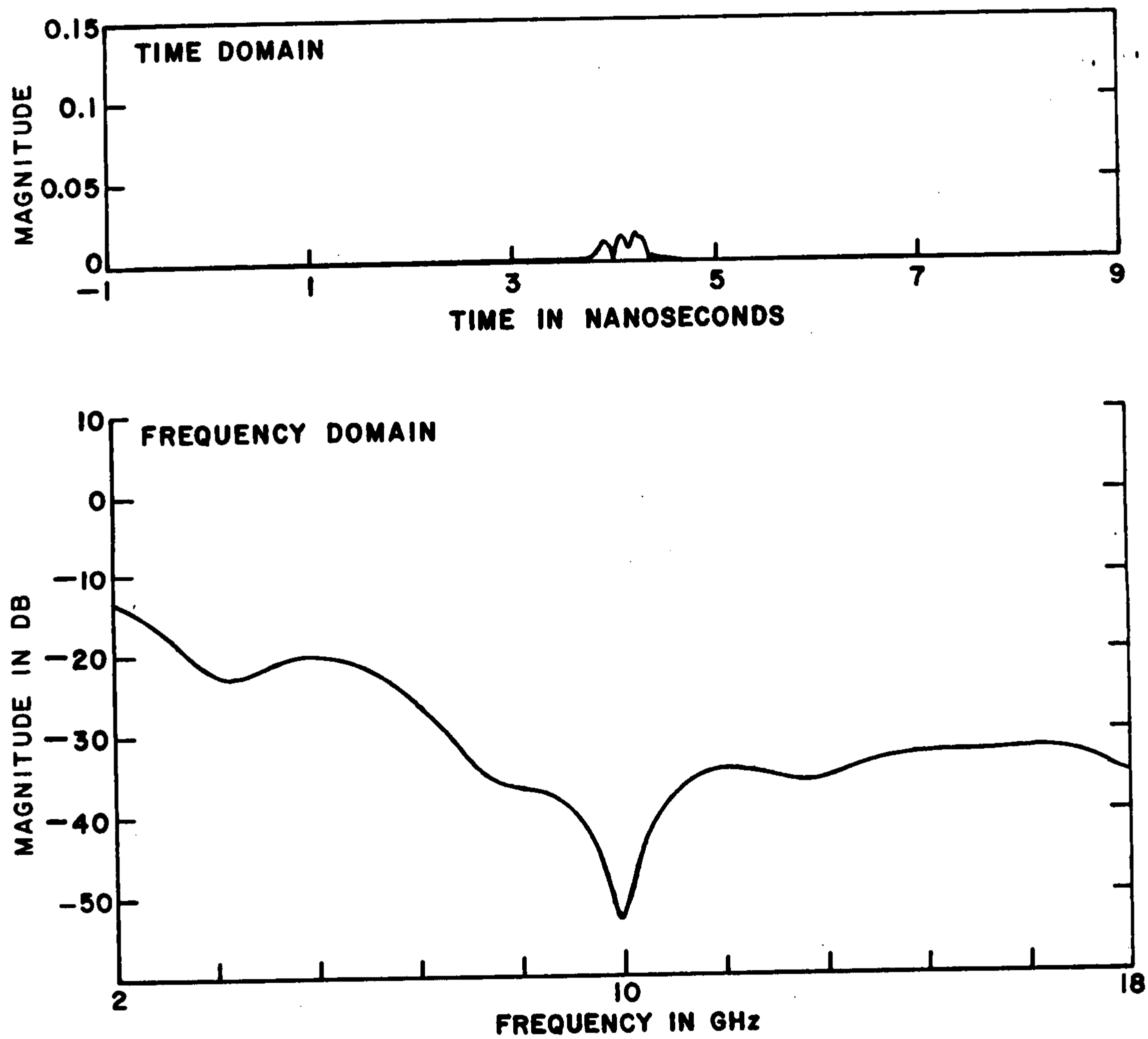

Figure 4.11: The measured, time gated reflected signal from the metal test sample support with material treatment using the AEL horn.

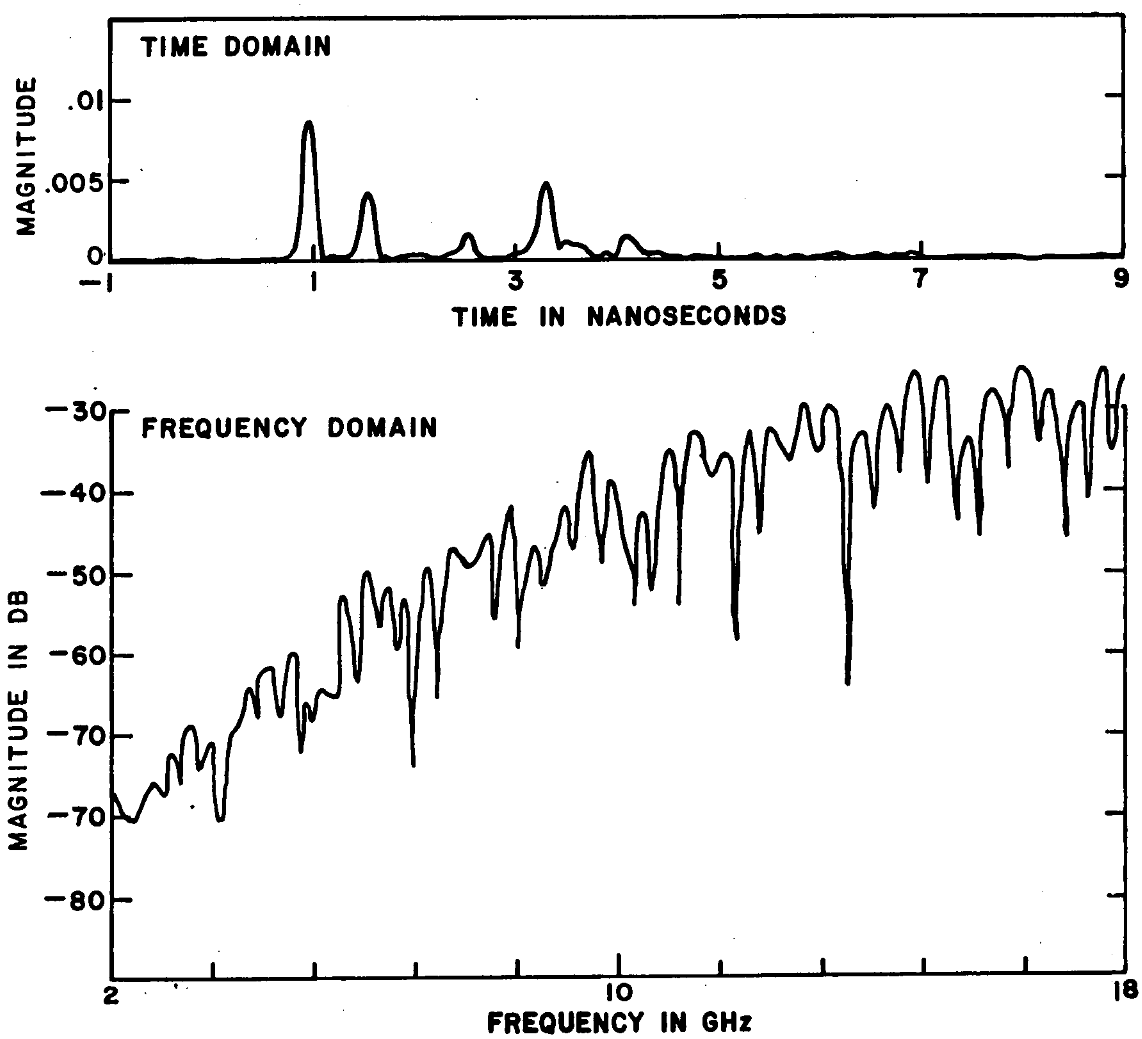

Figure 4.12: The measured surface wave signal on the metal test sample support with no material treatment and a 3" probe spacing.

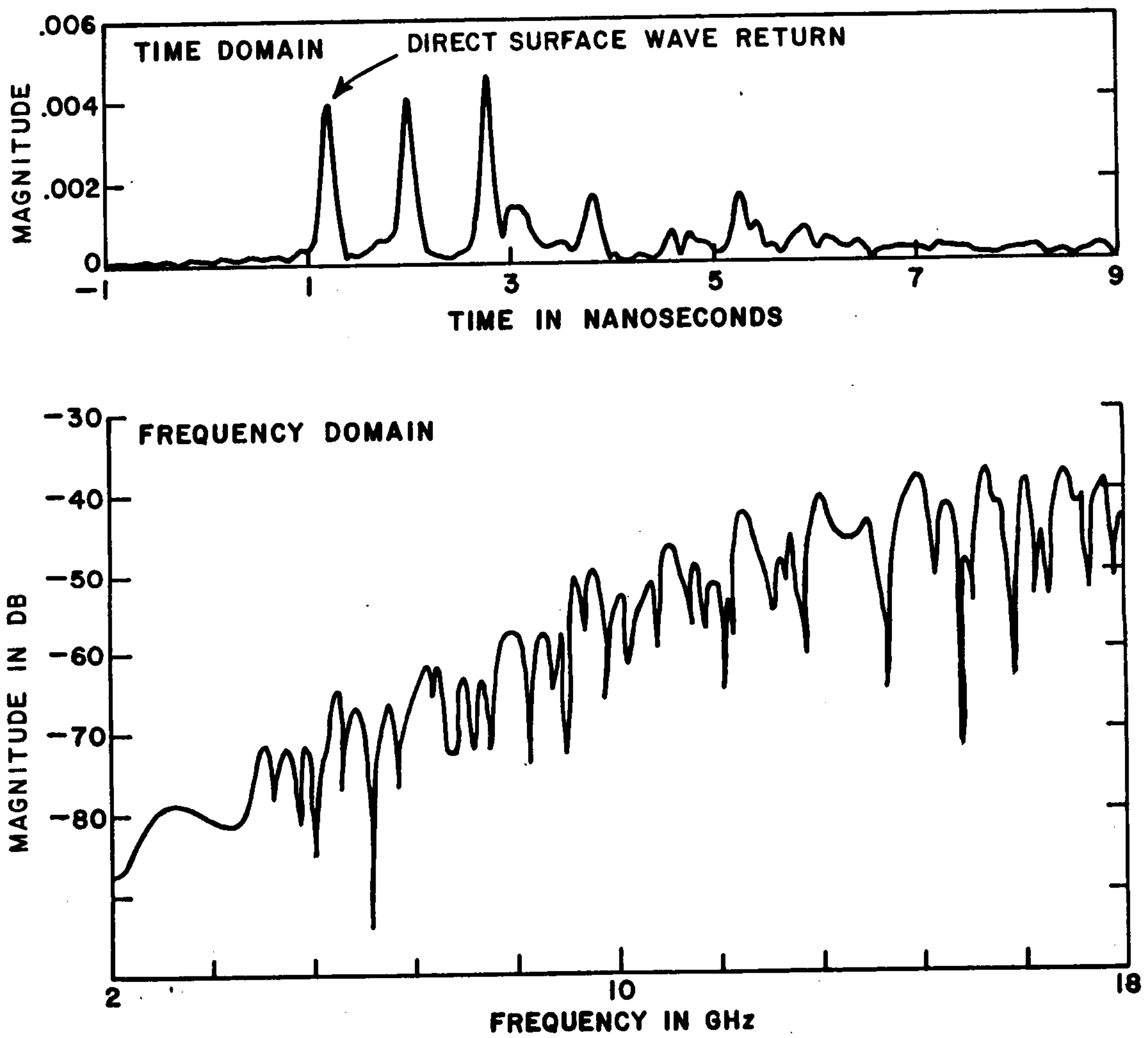

Figure 4.13: The measured surface wave signal on the metal test sample support with no material treatment and a 6" probe spacing.

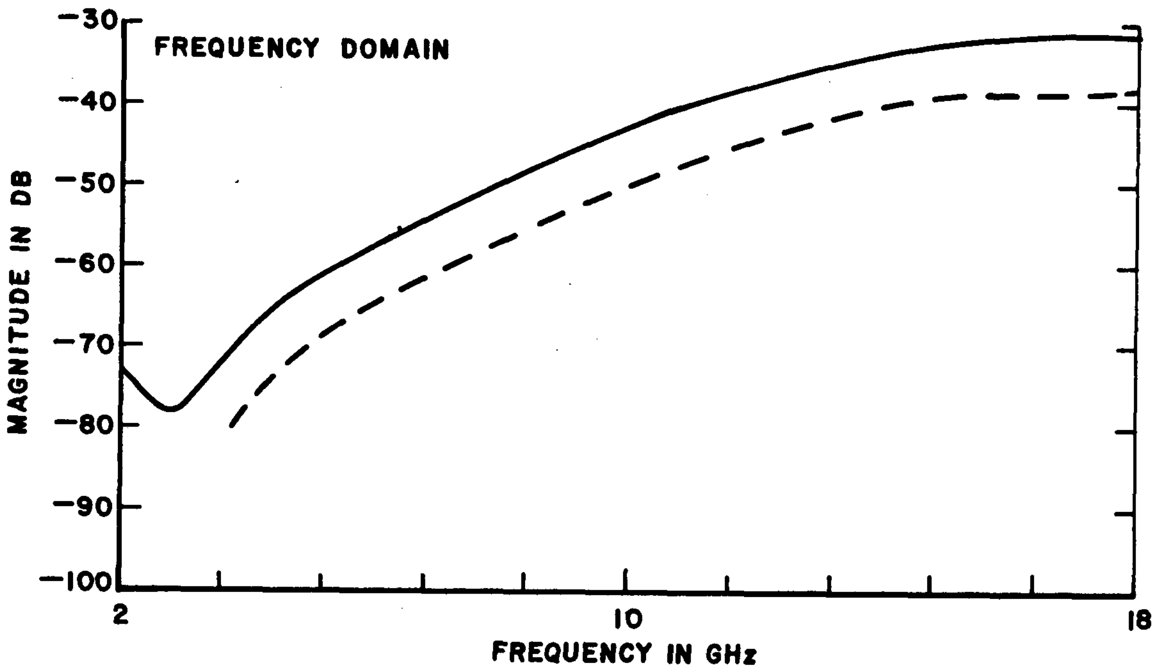

Figure 4.14: The measured, time gated surface wave signal on the metal test sample support with no material treatment. Probe spacing: 3" solid, 6" dashed.

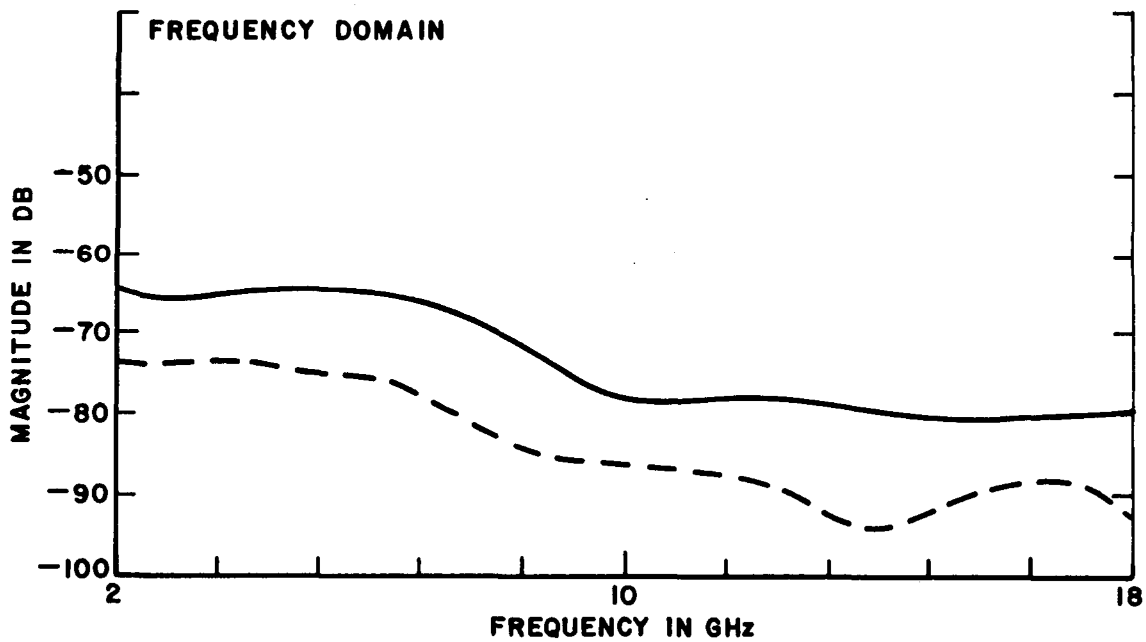

Figure 4.15: The measured, time gated surface wave signal on the metal test sample support with material treatment. Probe spacing: 3" solid, 6" dashed.

Chapter 5

Conclusions

Sensing the material changes can be achieved with either reflection or transmission measurements. Even though a transmission measurement would be more sensitive to the material parameters since the surface wave would have a longer path length than a reflected signal through a thin coating, it has been decided to place more emphasis on the reflection measurement approach due to the physical difficulty of using surface probes and maintaining a long usable probe life. The reflection measurement approach has the most likely chance of finding the material's parameters during the heat cycle test based upon the physical constraints of the two measurement approches. Acquiring the actual material parameters would be thwarted by not being able to supply a sufficiently stable calibration. This will not be known until the actual heat tests are performed. If the parameters can not be determined to characterize the electrical performance of the material, then at least the reflected signal can be monitored on a relative basis. The relative figure of merit can be either the frequency spectrum of the reflected signal or equivalently, the energy of the reflected signal in the time domain.

The programming of the HP computer is presently underway to perform the desired measurements and store the data.

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